

Wavelength Conversion up to 18 nm at 10 Gb/s by Four-Wave Mixing in a Semiconductor Optical Amplifier

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Abstract—We characterize the conversion bandwidth of a four-wave mixing semiconductor optical amplifier wavelength converter. Conversion of 10-Gb/s signals with bit-error-rate (BER) performance of $<10^{-9}$ is demonstrated for wavelength downshifts of up to 18 nm and upshifts of up to 10 nm.

Index Terms—Communication systems, frequency conversion, optical mixing, semiconductor optical amplifier.

A WORLDWIDE consensus is emerging on the use of wavelength-division multiplexing (WDM) technologies for more effective utilization of bandwidth in existing and future fiber-optic telecommunications infrastructure. A key element in the implementation of all-optical WDM systems is a wavelength converter [1]. Wavelength converters have been demonstrated utilizing a wide variety of mechanisms [2]. Optoelectronic, cross-gain saturation, and cross-phase saturation wavelength converters are candidate technologies that have demonstrated excellent performance. However, all of these converters suffer from the limitation that they are not transparent to either bit-rate or modulation format. Complete transparency is offered only by ultra-fast wave mixing techniques. Wavelength conversion by four-wave mixing (FWM) has been demonstrated in single-mode fiber [3], semiconductor lasers [4], and semiconductor optical amplifiers (SOA's) [5], [6]. Of these FWM converters, only the SOA allows a tunable pump source. For a wavelength converter to allow completely flexible switching between channels in a WDM system, a tunable pump is required in order to provide access to a continuous range of converted signal wavelengths.

A central issue to the implementation of FWM SOA wavelength converters is conversion efficiency. With third order susceptibilities five to seven orders of magnitude larger than that of silica fiber, it is possible to obtain useful conversion efficiencies in SOA's that are less than 1 mm in length [7]. The efficiency decreases with increased signal-pump wave detuning (more rapidly for wavelength upshifts than for downshifts due to destructive phase interference between the contributions

from the multiple mechanisms participating in the FWM process [8]). This, in turn, can prevent detection of the converted signal with a low bit-error rate (BER). Previous work has demonstrated conversion of 622-Mb/s signals over 20 nm [5], and 10-Gb/s signals over 4 nm [6]. Here, we demonstrate and characterize wavelength conversion of 10-Gb/s signals over a record 18-nm downshift and a 10-nm upshift. To our knowledge, this is the first reported system demonstration with a wavelength upshift by SOA FWM. In addition, we characterize the converter's power margin, or the difference between the in-fiber converted signal power at the SOA output and the power required at that wavelength shift for 10^{-9} BER performance.

The wavelength converter is shown in Fig. 1. The pump source is a tunable, external-cavity semiconductor laser with about +3 dBm in-fiber power. This pump source and the input signal are coupled together in a bidirectional coupler (BDC) after each individually goes through a mechanical polarization controller. The combined signals are then amplified in a high-power erbium-doped fiber amplifier (EDFA). The amplified signals are coupled through a 10-nm-wide bandpass filter (BPF). This is done to suppress the ASE from the EDFA in the spectral region of the converted signal. The ASE prefiltering, first described and demonstrated by Zhou *et al* [9], provides an increase in the optical SNR of the converted signal of over 5 dB. After ASE prefiltering, the pump and input signal are coupled into the SOA with a combined power of approximately +13 dBm. The SOA is a fiber pigtailed unit from SDL based on a multiquantum-well compressively strained gain medium with 25-dB fiber-to-fiber gain. The wavelength conversion efficiency is polarization dependent, and both the pump and probe polarizations must be aligned to the TE axis of the SOA. Following the SOA, these signals are coupled through a 1-nm-wide BPF to suppress the pump and input signal at the wavelength converter output.

To characterize the performance of this converter, it is introduced into the simple optical link shown in Fig. 1. Signal generation, error detection, and eye analysis are done with a 10-Gb/s bit-error-rate tester (BERT) and a microwave transition analyzer. The BERT generates a 10 Gb/s NRZ PRBS which is amplified and used to drive a LiNbO₃ Mach-Zehnder external modulator. This modulates the optical signal source, which in this case is a distributed feedback laser (DFB). The fixed wavelength of the DFB prevents us from being able to compare the converted signal performance to a baseline,

Manuscript received October 7, 1996; revised December 11, 1996. This work was supported by DARPA under Contract DAAL 01-94-K-03430 and the National Science Foundation under Grant ECS-9412862.

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Publisher Item Identifier S 1041-1135(97)02448-8.

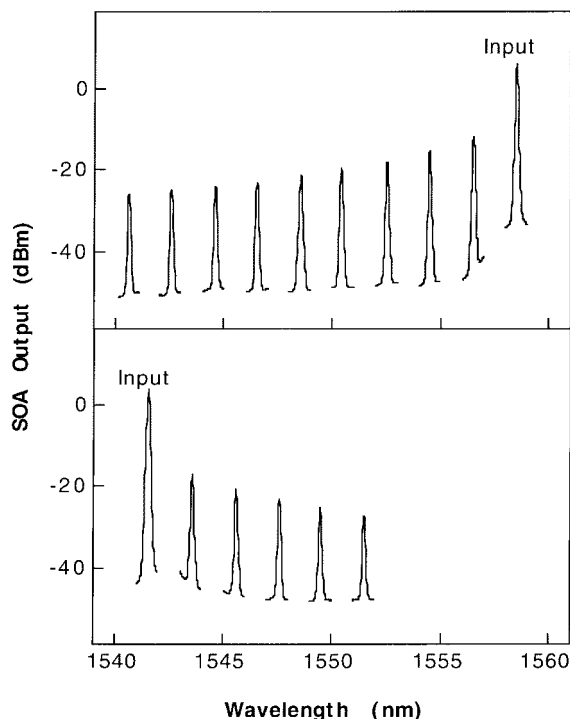
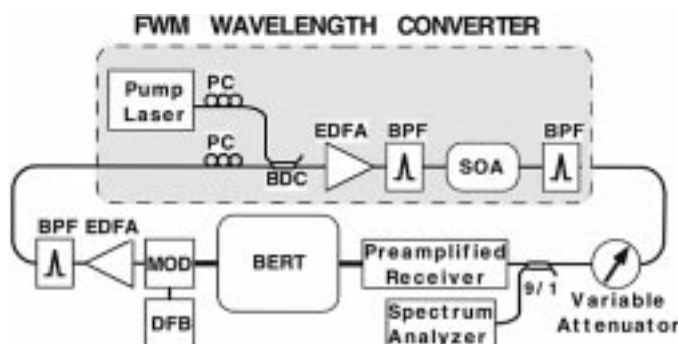


Fig. 2. Spectra of the original signal and the converted signals at the SOA output for the various wavelength shifts.

unconverted signal at the same wavelength. The optical signal is then amplified and filtered with an EDFA (followed by a BPF) to compensate for losses in the external modulator. The signal is then input to the wavelength converter. The converter output is first coupled through a variable attenuator and then a BDC tap. This allows us to take BER data for varying received powers, reading the received power of the converted signal into a 0.5-nm bandwidth on an optical spectrum analyzer connected to the tap. Finally, the converted signal is detected with a preamplified receiver, consisting of a high-gain, low-noise EDFA optical preamplifier, a 1-nm-wide BPF, a PIN detector and electrical amplifiers. The performance of the preamplifier has a small spectral dependence, which leads to slightly different slopes of BER plots for signals with different wavelengths.

The converter performance is characterized for shifts both up and down in wavelength. For the downshifts, our signal source has a wavelength of 1558.5 nm. The converter is characterized for downshifts every 2 nm from 2 to 18 nm. The spectra of the original signal and the converted signals at

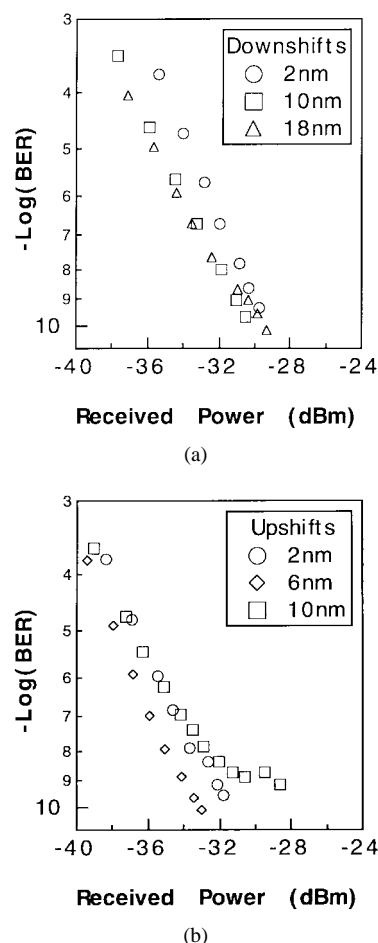


Fig. 3. BER versus received power curves for selected (a) downshifts and (b) upshifts.

the converter output are shown in the upper panel of Fig. 2. The ratio of the converted signal to the input signal at the SOA output falls from -17.9 dB for the 2 nm shift to -31.7 dB for the 18 nm shift. The background ASE in the region of the converted signal is approximately constant, rising somewhat for the 2-nm shift because of incomplete suppression of the EDFA ASE by the prefilter in this spectral range. The resulting converted signals have optical SNR's (into 0.1-nm bandwidth) ranging from 32 to 24.5 dB.

BER versus received power curves for downshifts of 2, 10, and 18 nm are shown in Fig. 3(a). For the 2-nm shift, the pump suppression by the BPF's at the converter output and in the preamplified receiver is not sufficient to prevent serious degradation of the receiver sensitivity. With a single filter, there is a received power penalty of approximately 3 dB when compared to the other conversions. Adding another filter in series for this shift improves the sensitivity by about 2 dB, bringing it to within 1 dB of the other curves. There are two features of note in the 18-nm downshift curve. First, there is a slight flooring due to the decreased optical SNR of the converted signal. Second, BER's $>10^{-7}$ actually occur at lower received powers than for smaller shifts with larger SNR. This behavior results from variance in the receiver performance for different input wavelengths.

The upshift performance of the converter is characterized beginning with a signal source at 1541.5 nm. For this laser,

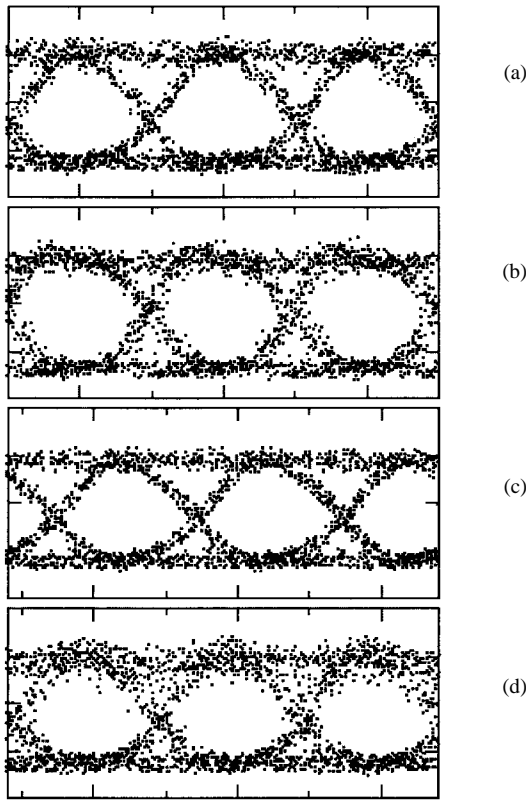


Fig. 4. Eye diagrams for (a) first DFB, no shift (b) first DFB, 18-nm downshift (c) second DFB, no shift (d) second DFB, 10-nm upshift.

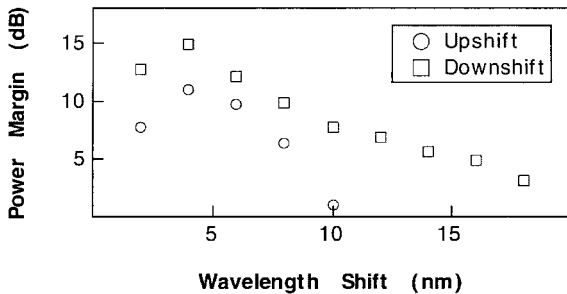


Fig. 5. Power margin for the converted signals.

upshifts every 2 nm from 2 to 10 nm are characterized. Original and converted signal spectra at the SOA output are shown in the lower panel of Fig. 2. The maximum ratio of the converted signal to the input signal at the SOA output is -21.0 dB for the 2-nm upshift. At a 10-nm upshift, this ratio has fallen to -31.1 dB. For both of these upshifts, the conversion efficiency is over 3 dB lower than for a downshift of the same magnitude. The resulting optical SNR's (into 0.1-nm bandwidth) range from 27.1 to 20.5 dB. BER measurements are taken for the various shifts, with tandem BPF's used again at the converter output for the 2-nm shift. Fig. 3(b) shows BER versus received power curves for upshifts of 2, 6, and 10 nm. The curves display characteristics similar to those for the downshift. Here, the floor at the maximum shift is more evident due to the much smaller optical SNR, occurring in the 10-nm shift at a BER of 7×10^{-10} .

For a qualitative analysis, Fig. 4 shows eye diagrams for (a) the unconverted signal at 1558.5 nm, (b) the signal downshifted by 18 nm, (c) the unconverted signal at 1541.5 nm, and (d) the signal upshifted by 10 nm. Clearly evident is the minimal degradation to the eye. There is almost no visible additional noise on the signal downshifted by 18 nm. The eye diagram for the 10-nm upshift exhibits a small amount of additional noise (more evident at the "1" level), however, it still remains wide open.

An important characterization of the wavelength converter performance that has not been previously reported is the power margin. The power margin of this converter as a function of wavelength shift is shown in Fig. 5. The decrease in power margin as the magnitude of the shift increases is primarily due to the decrease of the in-fiber converted signal power. This causes the power margin to drop from 15 dB at a downshift of 4 nm to 2 dB at a downshift of 18 nm and from 11 dB at an upshift of 4 nm to 1 dB at an upshift of 10 nm. The power margin maximum does not occur for the 2 nm shifts because of the increased power required for 10^{-9} BER performance due to poor pump suppression by the BPF at the SOA output.

The converter characterized in this work has demonstrated conversion of 10-Gb/s signals over a record span of 18 nm. We believe the enhanced performance of this device results from the use of high SOA input power in conjunction with ASE prefiltering. In characterizing both upshift and downshift capability, we have effectively demonstrated complete coverage of a 10-nm wavelength range by our converter. Thus, this wavelength converter would allow switching of any WDM channels within a 10-nm spectral range.

ACKNOWLEDGMENT

The authors acknowledge P. O. Hedekvist for invaluable discussion and assistance.

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